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SUBJECT: An Investigation of the 'Landing Accuracy' Detailed Objective - Case 310

DATE: January 25, 1971

FROM: W. W. Ennis

ABSTRACT

The desirability of a 'Landing Accuracy' Detailed Objective in Apollo Mission Requirements Document is discussed. It is shown that the Detailed Objective written for Apollo 14 and later deleted was not very responsive to the requirements, and that without such an Objective for Apollo 12 the results have been inadequately reported following that mission. The desired capability was in fact demonstrated in Apollo 12, but the failure of the reporting suggests the general conclusion that important questions required to be answered by a mission should be carefully worked out and formally stated in the medium established for the purpose: the Mission Requirements Document.

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MEMORANDUM FOR FILE

A Detailed Objective named "Evaluation of Landing Accuracy Techniques" was part of the Mission Requirements originally approved for the Apollo 14 (H-3) mission. The purpose of this objective was "to evaluate significant trajectory control techniques that affect the ability to land at a preselected lunar feature." The sole functional test objective was to "obtain data to allow a determination of the ability to land within one kilometer of a preselected lunar feature." The Test Conditions, Success Criteria, Evaluation, Data Requirements, and Background and Justification sections followed in the customary format. The Evaluation in particular was laid out in great detail; this will be discussed later.

Some Manned Spacecraft Center personnel have opposed the inclusion of a Landing Accuracy objective in Mission Requirements. Their position has been that the landing accuracy capability was adequately demonstrated in the Apollo 12 mission and that the published analyses and reports on that mission (i.e., References 1 and 2) represent an adequate write-up of the objective (although it was not part of the Requirements for that mission). In October, 1970 the objective was officially deleted from the Mission Requirements for Apollo 14.

This memorandum reports the results of an examination of the Landing Accuracy objective originally specified for Apollo 14 and of an evaluation of the reports and analyses on Apollo 12 that would be relevant to that objective had it applied to that mission.

The Landing Accuracy Objective

Hindsight suggests that the objective as written for Apollo 14 was not very well worked out for the purposes at hand. The Evaluation section of this objective requires first that "the location of the landed LM with respect to the preselected lunar coordinates shall be determined." This and the subsequent requirements do not recognize that the "preselected lunar coordinates" and the coordinates in which the LM flies and lands are measured in different--and uncertainly related--systems (see Appendix 1). The next evaluation requirement is that the LM trajectory data will be evaluated, along with various sets of landing site coordinates, to "isolate" the effects of each trajectory control technique (state vector update, RLS update, and ΔRLS). It is not clear what is to be gained by isolating the effects of these techniques, even if it could be done. Nevertheless, seven sets of artificial technique-isolating coordinates are required, each specified in the form, "Extrapolated landing coordinates using the * * * technique(s) (corrected for redesignation if applicable)." This kind of analysis ignores the statistics and uncertainties, as well as the disturbances that produce inconsistencies between measurements made in different orbits or in different passes of the same orbit (see Appendix 2). The final section of the Evaluation requirements concerns the effects on propellant consumption of using the SPS for DOI and of flying the descent trajectory with increased horizontal velocity at low gate. These matters were perhaps added as an afterthought and in any case do not apply to Apollo 12.

Landing Accuracy Capability as Demonstrated and Reported in Apollo 12

A reasonable "Evaluation" requirement for a Landing Accuracy mission objective should address specifically the capability of reaching a landing at, or acceptably near to, a preselected point. The preselected points arising in the Apollo Program are picked out on the highest-resolution surface photographs available, on the bases of interest and landing feasibility. They are therefore associated primarily with visible physical surface features, and only artificially with any sets of numbers called coordinates. The spacecraft and trajectory design afford the LM crew considerable freedom to observe the area being approached and to redesignate the automatic landing target in the last 100 seconds of the automatically guided part of the descent, and to maneuver to a landing point of their choice after assuming manual control. The ability of LM crews to do this--given sufficient time, suitable lighting conditions, etc.--has been demonstrated twice on the Moon and many times in simulation and is not at issue in this memorandum. The question of the capability of landing at a preselected point is then that of the capability of the system to reliably bring the crew within redesignation and manual maneuver range of a designated feature of the lunar surface.

There is no question that in the Apollo 12 mission the system did bring the LM and crew within range of the preselected point and that a landing was made at the desired place. The LM touched down a little over 500 feet northwest of the Surveyor, on the rim of the crater in which the Surveyor stands. The Surveyor itself was the targeted landing point. An analysis by MSC (Reference 2) states that the target (i.e., the target coordinates in the LM guidance computer) was 170 feet too far south and 380 feet too far west, or, if a deliberately neglected 310-foot additional correction were included, 250 feet too far south and 80 feet too far west. This spectacular success and this kind of rather complacent analysis have tended to obscure the possibility that a number of potentially large errors just happened to be small or to cancel each other out; in other words, the possibility that the Apollo 12 success was a fluke resulting from the conspiracy of the statistics, and next time we may receive a horrid surprise. So the key word in the statement of the relevant question becomes reliably; it is necessary to examine the errors (dispersions) in the inputs that are critical to arrival at the automatic delivery point.

These errors may be divided conveniently if not very rigorously into errors in LM position and velocity and errors in landing site position. These terms depend on the coordinate system assumed but both mean errors in the coordinates in the LM computer. If it is assumed that the landing site's coordinates are really those the LM computer is using for it--i.e., that the error in the landing site position is zero--then, by definition, any discrepancies lie entirely in the LM computer's idea of its own position in the coordinate system it is using. If, on the other hand, it is decided that the LM computer knows its own state vector in its coordinate system perfectly, all discrepancies lie in the landing site coordinates held in the computer. The real-life situation in the landing pass is generally no such simple case, however; it will be more like the following:

a) The position of the landing site has been calculated from optical observation data taken from the CM. The coordinates computed for it are therefore in the coordinate system determined by the tracking data processing and fitting in the pass in which the observations were made.

b) There are errors of observation in the landing site position determination described above.

c) Because of the incomplete gravity model (and other unmodelled perturbations) the LM computer propagates its own trajectory inaccurately. In a short time (e.g., one revolution) after a "perfect update" the coordinates calculated by the LM for itself will become seriously in error.

d) The coordinate system in which the LM's trajectory is currently being tracked, fitted, and computed will also change slightly in each pass, thus drifting away from the system in which the update was made.

e) The system in which the landing site coordinates (with their observational uncertainties) are known may also be different from that of the update, depending on which pass the sightings were made in.

To assure accurate landing point targeting, therefore, it is necessary to update the LM state vector as late as possible, in the coordinate system in which the landing site position has been observed (or as close to it as we can get). The techniques adopted with such success in Apollo 12 to accomplish these ends were:

1. Determination of the relative position of the CSM (and LM) with respect to the landing site by landmark tracking in a late pre-descent pass. This determines landing site coordinates (RLS) in the system of the existing spacecraft orbit and tracking analysis.

2. An update of the LM state vector early in the landing pass, based on the pass-to-pass propagation errors determined in the previous revolutions.

3. A final correction (ΔRLS) to the LM position, entered just after Powered Descent Initiation (PDI). This correction is applied only to the downtrack coordinate and for convenience is entered as an adjustment to the targeted landing point coordinates rather than to the LM coordinates.

The errors entering critically into the LM's automatic arrival at the designated feature on the lunar surface are then:

1. Landmark tracking errors, i.e., the error in the measurement of the position of the designated feature.

2. The error in the updated state vector entered into the LM guidance in the landing pass.

3. The error in the final correction, applied to the landing site coordinates, at the beginning of the powered descent.

4. The error accumulated during the powered descent.

The only ones of these that appear to be significant under nominal conditions are No. 1 and No. 4 (Appendix 2). Apollo tracking is of such precision that even though no single fit is very good in the sense that it describes the spacecraft motion accurately over a long period of many revolutions, the differences between a propagated fit and the next fit can be determined very accurately. In addition, there are many passes of data available for comparison in various combinations before PDI, so that the propagation errors per pass and the trends in the errors can be determined with good confidence (Reference 5). The final downtrack correction or ΔRLS is determined primarily from the difference between the LM altitude rate from the current fit and that from the LM computer; this quantity is monitored for about 5 minutes before PDI so that an accurate and consistent value may be derived. The measurement is very sensitive and is shown by its agreement with the two backup modes of determination (References 5 and 6) as well as its self-consistency to be very dependable.

If the significant errors of Appendix 2 are combined in a root-sum-square, the result is a 99% probability ellipse with a semi-axis of 3440 feet (just over one kilometer) in the downtrack dimension and 4120 feet crosstrack.

Conclusions

It may be concluded that if ground tracking and data handling and processing are nominal (including the late updates to the LM), and if good sightings are obtained on the landing site in pre-descent passes, the probability that the guidance system would bring the LM to a landing within 1 km of the designated point is close to 99%, and therefore the probability that the LM will be within redesignation range of the desired point at hi-gate is satisfactory. The automatic guidance landing error ellipse now being cited by MSC for Apollo 14 has semi-axes 3400 feet downtrack by 4500 feet crosstrack, in good agreement with the numbers above.

It may further be concluded that the desired landing accuracy capability was demonstrated in the Apollo 12 mission, and that the data reported support that conclusion.

The information needed to reach these conclusions is not presented in any single document, however, nor is it readily available. Neither does there appear to be any published analysis leading to or supporting the technical conclusions. While the inclusion of a landing accuracy objective in this mission's requirements would not have guaranteed the information and analyses being presented in more relevant forms or assembled into one document, the inference is inescapable that a formal statement of such an objective would at least establish official interest in and need for an answer to the question.

While the work reported in this memorandum and other published papers lead the author to conclude that the landing accuracy capability does exist and has been demonstrated, and that therefore there would be nothing to be gained by reinstating the objective for Apollo 14, another more general managerial conclusion is also suggested. If there is official interest in a mission problem, of such nature that answers are required to questions involving mission operations and mission-generated data, it is essential that the problem and the questions be adequately worked out and formally incorporated into the Mission Requirements as a Detailed Objective. While this does not guarantee an adequate response, its absence practically guarantees no response.

William Ennis

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Attachments

APPENDIX I

MAP COORDINATES VS APOLLO REAL-TIME COORDINATES

The "preselected lunar coordinates" come from a map. The map consists of a pictorial representation of a part of the lunar surface, with a grid of numbered lines overlaid. When a point or feature is selected, numbers or coordinates are assigned to it by interpolation between the numbers on the grid lines. The numbers on the grid lines are derived from coordinates calculated for the Lunar Orbiters that made the photographs from which the map was constructed. Those coordinates were derived from the tracking analyses of the Orbiters in their photographic passes in their various orbits. The LM flies (i.e., its trajectory is determined and its coordinates are reported) in a different coordinate system defined in the course of tracking the Apollo spacecraft, pass by pass, in the orbit in which they have been inserted for the mission in progress. That the coordinate systems are really different is shown by the almost unvarying finding that differing coordinates are generated for the same point when the vehicle trajectory and the tracking data processing are changed. An example is the variation of the tracking residuals with the lunar gravitational potential model used as well as with the spacecraft orbital characteristics. Another and immediately relevant example is the fact that the best "map" (i.e., Orbiter-determined) position of Surveyor III was about 1.5 km from the position determined by optical observations from the Apollo 12 CSM; the position as determined by JPL from tracking of the Surveyor was at still a third point about a kilometer distant from both of the other two. It appears then that the position of the landed LM with respect to the preselected lunar coordinates is not very meaningful or useful. The position of the actual landed LM with respect to the actual Surveyor III of course defines the relative accuracy of the achievement of the landing intentions, regardless of the coordinate systems used.

APPENDIX II

UNCERTAINTY ENTERING DESCENT TARGETING

The updated landing site position (RLS) is derived from the "best" pre-descent CSM observation of the intended landing point (or a landmark associated with it) from orbit. Examination of all of the position observations of Surveyor III and the landed LM in Apollo 12 (References 2, 4, 7) indicates that the probable error of a ground position determined by a single observation is about 1200 ft downtrack and about 1000 ft crosstrack; the 99% points are about 3100 ft downtrack and 2500 ft crosstrack. An uncertainty of this magnitude in this critical quantity cannot be neglected in an evaluation of the capability of landing at or near a selected point on the lunar surface.

A pre-mission landing dispersion analysis (Reference 3) (a Monte Carlo simulation) predicted a 99% dispersion ellipse 0.24 nm (1450 ft) downtrack by 0.54 nm (3300 ft) crosstrack, propagating from a perfect update just before PDI. These uncertainties therefore reflect the effects of the errors included in the simulation over the segment of the trajectory from PDI to landing. The simulation took into account PGNCS errors, terrain variations, DPS variations, and landing radar errors. It did not allow for any perturbations due to the unpredicted lumpiness of the lunar gravity.

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3. Apollo 12 (Mission H-1) Spacecraft Dispersion Analysis, Volume IV, Descent and Ascent Dispersion Analyses, Part 1, Lunar Descent, MSC Internal Note No. 69-FM-275, October 31, 1969.

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6. Computation of NOUN 69 in Rev. 14 of Apollo 12, H. G. de Vezin, Jr., MSC 69-FM46-383, November 26, 1969.

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